

THE LOCAL BLACK HOLE MASS FUNCTION DERIVED FROM THE $M_{BH} - P$ AND THE $M_{BH} - N$ RELATIONS

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ABSTRACT

We present a determination of the supermassive black hole (SMBH) mass function for early- and late-type galaxies in the nearby universe ($z < 0.0057$), established from a volume-limited sample consisting of a statistically complete collection of the brightest spiral galaxies in the southern hemisphere. The sample is defined by limiting luminosity (redshift-independent) distance, $D_L = 25.4$ Mpc, and a limiting absolute B-band magnitude, $\mathfrak{M}_B = -19.12$. These limits define a sample of 140 spiral, 30 elliptical (E), and 38 lenticular (S0) galaxies. We established the Sérsic index distribution for early-type (E/S0) galaxies in our sample. Davis et al. (2014) established the pitch angle distribution for their sample, which is identical to our late-type (spiral) galaxy sample. We then used the pitch angle and the Sérsic index distributions in order to estimate the SMBH mass function for our volume-limited sample. The observational simplicity of our approach relies on the empirical relation between the mass of the central SMBH and the Sérsic index (Graham et al. 2007) for an early-type galaxy or the logarithmic spiral arm pitch angle (Berrier et al. 2013) for a spiral galaxy. Our SMBH mass function agrees well at the high-mass end with previous values in the literature. At the low-mass end, while inconsistencies exist in previous works that still need to be resolved, our work is more in line with expectations based on modeling of black hole evolution.

Subject headings: galaxies: spiral — galaxies: elliptical and lenticular, cD — galaxies: structure — galaxies: fundamental parameters — galaxies: nuclei

1. INTRODUCTION

Rapid technological developments since the early 1990s have provided us with an enormous amount of information about the existence of Supermassive Black Holes (SMBHs; $M_{bh} \sim 10^5 - 10^9 M_\odot$) in almost all galaxies (Kormendy & Richstone 1995). Studies have shown that there is a correlation between the SMBH mass and a number of measurable features of the host galaxy due to the interaction between the SMBH and its surroundings. Some of the properties known to correlate well with the SMBH mass are the bulge luminosity (L_{Bulge} ; Kormendy & Richstone 1995; Marconi & Hunt 2003), the bulge mass (M_{Bulge} ; Kormendy & Richstone 1995; Marconi & Hunt 2003; Häring & Rix 2004), the mean velocity dispersion (σ) of the bulge stars (Ferrarese & Merritt 2000; Gebhardt et al. 2000), the Sérsic index (n) of the major-axis surface brightness profile (Graham & Driver 2007), and the pitch angle (P) of spiral arms in disk galaxies (Seigar et al. 2008; Berrier et al. 2013).

Over the past decade, the number of galaxies with secure mass estimates has increased, because studies have revealed new scaling relations and revised the existing ones, thus improving our understanding of galaxy-black hole coevolution. The substructures in the most commonly cited black hole scaling relations (e.g. $M_{bh}-L_{Bulge}$, $M_{bh}-\sigma$, $M_{bh}-M_{Bulge}$) are reported due to the barred

galaxies and/or pseudobulges. The true nature of galaxy evolution in different galaxy types still needs to be resolved.

A common practice with these correlations is to estimate the mass function of the central SMBHs (BHMF) in the local universe (e.g. Salucci et al. 1999; Yu & Tremaine 2002; Marconi et al. 2004; Shankar et al. 2004; Graham et al. 2007; Vika et al. 2009; Davis et al. 2014). A robust BHMF helps to describe the evolution of the SMBH distribution and provides important constraints on the coevolution of the quasar and black hole populations. The most well-known theoretical constraints are on the integrated emissivity of the quasar population, integrated mass density of black holes, and the average black hole accretion rate (Soltan 1982; Fabian & Iwasawa 1999; Elvis et al. 2002; Shankar et al. 2009). A comparison among the recent local BHMF estimates derived from different scaling relations can be seen in Figure 5 of Shankar et al. (2009). Most of these studies use an analytic approach, which combines the measurements of the galaxy luminosity or velocity function with one of the SMBH scaling relations as outlined by Häring & Rix (2004). These studies use some assumptions of the morphological type fractions and the bulge-to-total luminosity (B/T) ratios. The sensitivity of the low-mass end of the BHMF based on these assumptions is well presented in Figure A2 of Vika et al. (2009). Recently, Davis et al. (2014) estimated the BHMF by using the SMBH mass versus spiral arm pitch angle relation for a nearly complete sample of local spiral galaxies in order to produce reliable data for the low-mass end of the local BHMF. In this paper, we aim to estimate a local BHMF for all galaxy types within the same volume limits in order to complement this late-type

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BHMF. Therefore, we used the identical sample selection criteria used by Davis et al. (2014).

The structure of the paper is as follows: in Section 2, we discuss the robustness of the M_{bh} - P relation for late-type galaxies and the M_{bh} - n relation for early-type galaxies (E/S0). In Section 3, we describe our sample selection and its completeness. In Section 4, we present our methodology for estimating BHMF. We first describe how we measure the Sérsic indices and how we establish the Sérsic index distribution for the early-type galaxies in our sample. Then, we show our determination of the local BHMF from the Sérsic index distribution for the early-types and the pitch angle distribution for the late-types. Finally, in Section 5 we compare our results to the previous works.

A cosmological model with $\Omega_\Lambda = 0.691$, $\Omega_M = 0.307$, $\omega_b = 0.022$ and $h_{67.77} = H_0/(67.77 \text{ km s}^{-1} \text{ Mpc}^{-1})$ is adopted throughout this paper.

2. M_{BH} - P RELATION AND M_{BH} - N RELATION

A common conclusion based on observational data is that SMBHs are associated with the mass of the central bulge in the host galaxy. The M_{bh} - M_{Bulge} , M_{bh} - L_{Bulge} , and M_{bh} - n relations all depend on the success of the measurements of the central bulge. In late type galaxies, there can be difficulties when it comes to isolating the central bulge from other components of galaxies (e.g. bars, disc, and spiral arms). In the study of disc galaxies, a standard practice is to assume a fixed value of B/T ratio. This introduces a bias on a BHMF such that SMBH mass is over-estimated in the late-type disc galaxies and under-estimated in early-type disc galaxies (Graham et al. 2007). Another approach is to use the average B/T ratios derived from $R^{1/n}$ -bulge + exponential-disc decompositions (Graham et al. 2007), which requires heavy image processing tools. The large scatter in these relations to estimate SMBH mass can be traced back to the complexity of the decomposition in late-type galaxies, particularly in barred galaxies. The M_{bh} - σ relation has had considerable success in estimating SMBH masses in many galaxies. However, it requires spectroscopic measurements, which are observationally expensive and depend on the spectroscopic bandwidth. Furthermore, a careful approach is needed such that a consistent bulge region is always sampled for the measurement of σ . Similar to the above relations, measuring σ is more complex for disc galaxies than it is for elliptical galaxies because the velocity dispersion from the motion of disc and bar is coupled with σ and they need to be handled properly (Hu 2008).

Among other relations, the M_{bh} - P relation seems promising for late-type galaxies. Berrier et al. (2013) established a linear M_{bh} - P relation for local spiral galaxies as $\log(M/M_\odot) = (8.21 \pm 0.16) - (0.062 \pm 0.009)|P|$ with a scatter less than 0.48 dex in all of their samples. This is lower than the intrinsic scatter (≈ 0.56 dex) of the M_{bh} - σ relation, using only late-types (Gültekin et al. 2009). The P derived SMBH mass estimates also seem to be consistent in galaxies with pseudobulges, where other relations seem to fail (Berrier et al. 2013). Although there are obvious advantages in using the M_{bh} - P relation in late-type galaxies (see Discussion in Berrier et al. (2013)), one needs to use a complementary relation for elliptical and S0 galaxies since the M_{bh} - P relation is just applicable for spiral galaxies. Figure 6 in Berrier et al.

(2013) presents evidence that n and P derived mass estimates are compatible for non-barred galaxies, and a combination of these two approaches (i.e. using Sérsic index for E/S0 galaxies, and pitch angles for spiral galaxies) may produce a very accurate BHMF for all galaxy types by using only imaging data.

Graham et al. (2001) presented evidence that the light concentration of the spheroids correlate well with their SMBH mass, showing that more centrally concentrated spheroids have more massive black holes. Given that the Sérsic index, n , is essentially a measurement of the central light concentration, Graham & Driver (2007) found a log-quadratic relation between n and M_{bh} :

$$\log(M_{bh}) = (7.98 \pm 0.09) + (3.70 \pm 0.46) \log\left(\frac{n}{3}\right) - (3.10 \pm 0.84) \left[\log\left(\frac{n}{3}\right)\right]^2 \quad (1)$$

with an intrinsic scatter of $\epsilon_{intrinsic} = 0.18^{+0.07}_{-0.06}$ dex.

Recently, Sani et al. (2011), Vika et al. (2012) and Beifiori et al. (2012) failed to recover a strong M_{bh} - n relation. Savorgnan et al. (2013) re-investigated and recovered the relation using a large collection of literature Sérsic index measurements using R-band (Graham & Driver 2007), I-band (Beifiori et al. 2012), K-band (Vika et al. 2012), and $3.6\mu\text{m}$ (Sani et al. 2011) imaging data. Savorgnan et al. (2013) discussed the systematic effects associated with measuring Sérsic index in different optical and infrared wavebands. They concluded that the differences expected from measuring Sérsic index in different wavebands are smaller than the differences expected due to other systematic biases such as one-dimensional decomposition versus two-dimensional decomposition, or the differences between measuring the Sérsic index along a minor axis versus measuring it along a major axis. Indeed, one might expect that a Sérsic index measured using a one-dimensional fit (as performed in this paper) to be $\sim 10\%$ smaller than that measured using a two-dimensional fit (Ferrari et al. 2004). Furthermore, when measuring Sérsic index in multiple wavebands for the same galaxies, Savorgnan et al. (2013) found that wavelength bias was completely dominated by these other biases, which could be as large as 50%. Given, the result of Kelvin et al. (2012), we would expect the Sérsic index measured at $3.6\mu\text{m}$ to be less than 10% higher than that measured in the R -band, which is significantly smaller than the 50% number given by Savorgnan et al. (2013). Savorgnan et al. (2013) excluded the outlying Sérsic indices, averaged the remaining values, and recovered the M_{bh} - n relation by showing that elliptical and disc galaxies follow two different linear M_{bh} - n relations. They discussed how this relation is consistent with what would be derived by combining the M_{bh} - L_{Bulge} and L_{Bulge} - n relations and how this explains the log quadratic nature of the M_{bh} - n relation reported by Graham & Driver (2007).

In this paper, we define early-type galaxies as elliptical and S0 galaxies. The sample used by Graham & Driver (2007) was dominated ($\sim 89\%$) by elliptical and S0 galaxies. However, Savorgnan et al. (2013) studied S0 galaxies together with spiral galaxies. Therefore, we used the log quadratic M_{bh} - n relation reported by Graham & Driver (2007) to estimate SMBH masses in our

early-type sample.

3. DATA AND SAMPLE SELECTION

Davis et al. (2014) based their selection criterion on the Carnegie-Irvine Galaxy Survey (CGS) (Ho et al. 2011); it is an almost complete sample of 605 nearby galaxies in the southern hemisphere. Using the spiral galaxies in this parent sample plus Milky Way, they defined a volume-limited sample which consists of spiral galaxies within a luminosity (redshift-independent) distance of 25.4 Mpc and a limiting absolute B-band magnitude of $\mathfrak{M}_B = -19.12$. We followed the same selection criterion, except also including elliptical and S0 galaxies. As a result, our volume-limited sample consists of 208 host galaxies (30 ellipticals and 38 S0s and 140 spiral galaxies) within a comoving volume of $V_c = 3.37 \times 10^4 h_{67.77}^{-3} \text{ Mpc}^3$ over a lookback time, $t_L \leq 82.1 \text{ Myr}$. We then downloaded images of selected galaxies from the NASA/IPAC Extragalactic Database (NED).

A complete sample selection is necessary to estimate a meaningful BHMF. Therefore, we checked the completeness of our sample within the limits of luminosity distance and absolute B-band magnitude in several ways. First, we compared our sample size with the maximum number of galaxies within these limits. Figure 1 shows that the maximum number of galaxies, which is 217, appears at $D_L = 28.05 \text{ Mpc}$ and $\mathfrak{M}_B = -19.37$, whereas our sample consists of 208 galaxies. While these two limits just differ by 4%, using the limiting $\mathfrak{M}_B = -19.12$ allows us to include galaxies with dimmer intrinsic brightness, and helps us to be more complete.

In addition, we determined the luminosity function in order to check if our volume-limited sample is a fair representation of the local galaxy population over the absolute magnitude range $-19.12 \lesssim \mathfrak{M}_B \lesssim -23$. The luminosity function is determined as $\phi(\mathfrak{M}_B) = \partial N / \partial \mathfrak{M}_B$, where N is the number of galaxies in our sample in terms of the absolute B-band magnitude and dividing it by the comoving volume of the volume-limited sample. This is illustrated in Figure 2, which shows the comparison with the luminosity functions for the overall CGS sample (Ho et al. 2011) and the much larger sample of Blanton et al. (2003) and Bernardi et al. (2013). The luminosity functions of Blanton et al. (2003) and Bernardi et al. (2013) have been shifted by $B - r = 0.67 \text{ mag}$, the average color of an Sbc spiral (Fukugita et al. 1995), which is roughly the median Hubble type of both CGS and our volume-limited sample, and also transformed to $H_0 = 67.77 \text{ km s}^{-1} \text{ Mpc}^{-1}$. While Blanton et al. (2003) derived the luminosity function of $z \approx 0.1$ galaxies from Sloan Digital Sky Survey (SDSS) by using the Sérsic parameters from a 1-D radial surface brightness profile, Bernardi et al. (2013) derived it by using the 2-D fits to the whole galaxy image. The overall CGS sample has a luminosity function that agrees quite well with that of Blanton et al. (2003) (Ho et al. 2011). However, our galaxy sample has a luminosity function that implies that it was observed in an overdense volume (see red data points in Figure 2). Therefore, we renormalized our luminosity function by adding -0.25 in the y-axis in order to be consistent with that of Blanton et al. (2003) and CGS (see pink data points in Figure 2). For our BHMF estimation, we used the same normalization factor (see Section 4.3). In addition, due to the sample selection criterion, our luminosity

function does not extend below the magnitude limit of $\mathfrak{M}_B = -19.12$. This fact is obviously of interest to our BHMF estimation that will be discussed more in Section 5.

Furthermore, we compared the distribution of morphological types of CGS and our sample. Our morphological fractions, f_{type} , are as such: $f_E = 0.14$, $f_{S0} = 0.18$, and $f_{Spiral} = 0.67$. This is in good agreement with the ones ($f_E = 0.11 \pm 0.03$, $f_{S0} = 0.21 \pm 0.05$, $f_{Sbc+Sbc+Scd} = 0.62 \pm 0.14$) reported by Fukugita et al. (1998). Moreover, Figure 3 shows that our volume-limited sample preserves the distribution of morphological types in CGS. In addition, we checked the T-type distributions of CGS and our sample. The T-type values are taken from http://cgs.obs.carnegiescience.edu/CGS/database_tables. The differences between the densities of each T-type are always less than 5% (see Figure 4).

We used imaging data taken from the NASA/IPAC Extragalactic Database (NED) (see Table 3). The absolute magnitudes were calculated from apparent magnitudes, from *HyperLeda* (Paturel et al. 2003), luminosity distances compiled from the mean redshift-independent distance from the NED, and extinction factors in the B-band from Schlafly & Finkbeiner (2011), as compiled by the NED. We used several different band images for our measurements.

4. METHODOLOGY

4.1. Sérsic Index Measurement

In order to have a reliable Sérsic index measurement for early-type galaxies in our sample, we carefully masked the foreground stars and background galaxies by using the SEXTRACTOR (Bertin & Arnouts 1996), and determined the centers of the galaxies by using the IRAF task IMCNTR. The sky-background flux and its uncertainty were estimated from the mean and standard deviation of five median fluxes that were obtained from small boxes near the galaxy free corners of each images, respectively. Then, the surface brightness profiles were extracted using the IRAF task ELLIPSE (Tody 1986; Jedrzejewski 1987) with a fixed center and allowing the isophotal position angle and ellipticity to vary. The best Sérsic bulge + exponential disc model for S0 galaxies, and the best Sérsic bulge model for elliptical galaxies were fitted by minimizing χ^2 with an iterative procedure. The models were derived three times for each galaxy in order to estimate the Sérsic index error. The uncertainty in the sky-background level was respectively added and subtracted from the surface brightness profile data in the second and third derivation (see Figure 5). This method for estimating the errors on the model parameters was also used by de Jong (1996). When fitting the profiles, seeing effects are particularly relevant when the ratio between the FWHM of the seeing and the effective half-light radii R_e of the Sérsic model is small (Graham 2001). When $R_e/\text{FWHM} > 2$, the difference between the measured Sérsic index and the actual Sérsic index is typically small, as explained by Graham (2001). For our sample, all the derived bulge values for R_e are greater than $1''$, and the ratio R_e/FWHM is greater than 2 (see Table 3, Column 6). The results of the best-fitting Sérsic bulge model for elliptical galaxies and the best-fitting Sérsic bulge + ex-

ponential disc model for S0 galaxies are shown in Figure 6 and 7, respectively.

We successfully completed the Sérsic index measurements for all 68 galaxies in our sample. Before proceeding, we note that Equation 1 was constructed in the R-band (Graham & Driver 2007), while our data ranges from the R-band to $4.6\mu\text{m}$. The structural parameters of a galaxy may vary with wavelength due to the radial variations in stellar population and/or dust obscuration (Kelvin et al. 2012). This may result in different values for Sérsic index in different wavelengths. However, the local early-type galaxies mostly have fairly small color gradients (e.g. Peletier et al. 1990; Taylor et al. 2005). Using similar fitting method to ours (Sérsic bulge model for ellipticals; Sérsic bulge + exponential disc model for disc galaxies), McDonald et al. (2011) found that the Sérsic indices of elliptical and S0 galaxies show no significant variation across optical and NIR wavelengths. In order to quantify how photometric and structural parameters of a galaxy vary with wavelength, recent studies used 2D single Sérsic fits and reported that galaxies with different Sérsic indices and colors follow different trends with wavelength (e.g. Kelvin et al. 2012; Vulcani et al. 2014; Kennedy et al. 2015). Their common result is that high- n galaxies remain relatively stable at all wavelengths. These high- n galaxies roughly correspond to our early-type sample. However, it is worth mentioning that the measurement of the Sérsic index in these recent studies are different to ours: they used a single Sérsic profile fit for all galaxies and made no attempt to remove objects for which a two-component fit would be more appropriate. Therefore, single Sérsic index wavelength dependence mostly gives information about bulge and disc properties of a galaxy (Kennedy et al. 2016). For example, Vulcani et al. (2014) attributed the lack of variation in Sérsic index with wavelength for red galaxies to the fact that they principally comprise one-component objects (i.e. ellipticals) or two-component galaxies in which the components possess very similar colors, i.e. S0s. Although we can get some insight for the (disc-less) elliptical galaxies, the single Sérsic galaxy model is not suitable for quantifying possible changes with wavelength to Sérsic indices of bulges in S0 galaxies. Therefore, following the work of McDonald et al. (2011), we did not apply any corrections to our Sérsic index measurements. All measured data for individual early-type galaxies in our sample are listed in Table 3.

4.2. Sérsic index distribution

As a result of Sérsic index measurements, we had three Sérsic index estimates (n_i) for each of our 68 galaxies. We used two independent ways in order to find the best fit probability density function (PDF) to our data.

First, we employed a nominal *binless* histogram, which is identical to the method in Davis et al. (2014), in order to create the Sérsic index distribution. We modeled each data point twice as a normalized Gaussian, where the mean is the average Sérsic index values $\langle n_i \rangle$ and the standard deviation is the standard deviation of n_i , $\sigma_{\langle n_i \rangle}$. The Sérsic index distribution is obtained by a normalized sum of Gaussian values. Then, we repeated the same modeling, but this time the mean is the average logarithmic value of n_i , $\langle \log n_i \rangle$, and the standard deviation is the standard deviation of $\log n_i$,

$\sigma_{\langle \log n_i \rangle}$. From the resulting Sérsic index distributions, we were able to compute the statistical standardized moments of a probability distribution; mean (μ), standard deviation (stdev), skewness, and kurtosis. The two distributions give us almost the same statistical standardized moments: $\mu = 3.10(3.10)$, $stdev = 1.38(1.39)$, $skewness = 0.95(0.95)$, and $kurtosis = 4.17(4.18)$, where the numbers in parentheses refer to the distribution derived from $\langle n_i \rangle$ and $\sigma_{\langle n_i \rangle}$. We used the MATLAB code PEARSFDF to perform our PDF fitting. To explore the uncertainty in our PDF fit, we used a bootstrapping process. The random number generator NORMRND in MATLAB was used for sampling (with replacement) from the original 68 data points, using the mean as $\langle \log n_i \rangle$ and the standard deviation as $\sigma_{\langle \log n_i \rangle}$. The statistical standardized moments for one thousand data sets containing 68 data points each were individually calculated. This gave one thousand new estimates for each of the parameters (μ , stdev, skewness, and kurtosis). Then, the median and the standard deviation of these new estimates gave us the uncertainty on the PDF fitting: $\mu = 3.12 \pm 0.02$, $stdev = 1.40 \pm 0.04$, $skewness = 0.92 \pm 0.03$, $kurtosis = 3.87 \pm 0.30$.

Then, we used the MATLAB code ALLFITDIST, which fits all valid parametric probability distributions to the data and returns the fitted distributions based on the Bayesian information criterion. As a result, the gamma distribution function is given as a best PDF fit, with $\mu = 3.11$, $variance = 1.84$, shape $a = 5.26 \pm 0.51$, scale $b = 0.59 \pm 0.06$. The resulting Sérsic distribution and its PDF fits are illustrated in Figure 8.

4.3. Estimating BHMF

The local BHMF is formulated as

$$\phi(\log(M_{bh})) = \frac{\partial N}{\partial \log(M_{bh})} = \frac{\partial N}{\partial x} \frac{\partial x}{\partial \log(M_{bh})} = \phi(x) \frac{\partial x}{\partial \log(M_{bh})} \quad (2)$$

where N is the number of galaxies, x is pitch angle P for late-type galaxies and Sérsic index n for early-type galaxies, and M_{bh} is SMBH mass. For the early-type galaxies, the Sérsic index measurements for the volume-limited sample give us the Sérsic index function $\phi(n) = \frac{\partial N}{\partial n}$; and $\frac{\partial n}{\partial \log(M_{bh})}$ can be evaluated by taking the derivative of Equation 1 as follows:

$$\frac{d \log(M_{bh})}{dn} = \frac{(3.70 \pm 0.46)}{n \ln(10)} - \frac{2(3.10 \pm 0.84) \log(\frac{n}{3})}{n \ln(10)} \quad (3)$$

As a result, we get the following equation:

$$\phi(\log(M)) = \phi(n) \left[\frac{(3.70 \pm 0.46)}{n \ln(10)} - \frac{2(3.10 \pm 0.84) \log(\frac{n}{3})}{n \ln(10)} \right]^{-1} \quad (4)$$

Using Equation 5 and dividing by a local comoving volume of $V_c = 3.37 \times 10^4 h_{67.77}^{-3} \text{ Mpc}^3$, the Sérsic index distribution was converted into the BHMF for the early-type galaxies.

In order to estimate the error in the BHMF, we ran a Markov Chain Monte Carlo (MCMC) sampling of the BHMF. The sampling uses 10^5 realizations of the Sérsic index

distribution based on the errors in the previous section. The Sérsic index distributions were randomly generated from the parameters that define the PDF, assuming that they are normally distributed with the 1σ uncertainties given by the estimated errors. The uncertainties in the M_{bh} - n relation are also allowed to vary as a Gaussian distribution around the fiducial values. We first estimated the BHMF without assuming any errors, then we allowed the listed errors (four parameters in the PDF fit + three parameters in the M_{bh} - n relation) to be perturbed individually and collectively. This is illustrated in Figure 9 (left), which shows that the Sérsic index distribution has no impact on the BHMF for $M_{bh} > 10^9 M_\odot$ since the mass of the SMBH is fixed for $n > 11.9$. The sharp decrease at the high-mass end is the result of the curved nature of the M_{bh} - n relation, that predicts a maximum mass which SMBHs have formed (Graham et al. 2007). The uncertainties in the M_{bh} - n relation dominate at this region, softening the high-mass decrease of the BHMF, and thus increasing the total density of the BHMF for high masses.

The error region in the BHMF is estimated by the 16th and 84th percentile of the 10^5 MCMC realizations, similar to the method used by Marconi et al. (2004), where the 16th and 84th percentiles indicate the 1σ uncertainties on the logarithm of the local BHMF. In order to deal with the intrinsic scatter in the M_{bh} - P relation, Davis et al. (2014) used the method described in Equation 3 in the paper of Marconi et al. (2004). However, we did not adopt this method for our early-type BHMF. Graham et al. (2007) discussed that the intrinsic scatter in the M_{bh} - n relation is not Gaussian; and the removal of the two highest mass SMBHs converts the M_{bh} - n relation into one with zero intrinsic scatter. In estimating the BHMF derived from the M_{bh} - n relation, Graham et al. (2007) did not apply any correction for the intrinsic scatter, and neither did we. Finally, we obtained our best estimate of the early-type BHMF by merging all the random realizations of the BHMFs and considering the 16th, 50th, and 84th percentile levels (see the right panel in Figure 9). We note that the early-type BHMF is normalized by adding -0.25 in the y-axis, which corrects for the overdensity in our selected volume.

In order to estimate the local BHMF for all galaxy types, following Equation 3, we also run the MCMC realizations of the BHMF for the spiral galaxies, but this time using the pitch angle distribution that was derived by Davis et al. (2014). Note that Davis et al. (2014) estimated possible SMBH masses from the M_{bh} - P relation by using the MCMC sampling and then fitted a PDF model to derive the late-type BHMF. In this paper, we used the best-fit PDF model for the pitch angle distribution derived by Davis et al. (2014), and then used Equation 3 by adopting the method used by Marconi et al. (2004) to estimate the late-type BHMF by considering the 16th, 50th, and 84th percentile levels of the MCMC realizations. Similar to our early-type MCMC sampling, we assumed that the input parameters (μ , stdev, skewness, kurtosis) of the PDF fit and the uncertainties in the M_{bh} - P relation are Gaussian distributed around the fiducial values. Then, we merged all random realizations of BHMFs from the early-type and spiral galaxies. Figure 10 shows our best estimate of the local BHMF obtained by merging all

random realizations and considering the 16th, 50th, and 84th percentile levels. The late-type BHMF and the early-type BHMF are also shown in Figure 10 to help visualize how the early- and late-type samples are being spliced. We note that the our BHMF estimates are all normalized by adding -0.25 in the y-axis to be able correct for the overdensity in our survey volume. The plotted data for Figure 9 (right) and Figure 10 are listed for convenience in Table 1.

4.4. SMBH mass density

Integrating over the mass functions, we derived the local mass density of SMBHs which gives $1.74^{+0.79}_{-0.60} \times 10^5 h_{67.77}^3 M_\odot \text{ Mpc}^{-3}$ for early-type and $2.04^{+1.16}_{-0.75} \times 10^5 h_{67.77}^3 M_\odot \text{ Mpc}^{-3}$ for all-type galaxies. For reference, Graham et al. (2007) and Vika et al. (2009) reported $3.99 \pm 1.54 \times 10^5 h_{67.77}^3 M_\odot \text{ Mpc}^{-3}$ and $7.25 \pm 1.18 \times 10^5 h_{67.77}^3 M_\odot \text{ Mpc}^{-3}$ for the SMBH mass density in the local all-type galaxies, respectively. In terms of the critical density of the universe, we obtained $\Omega_{BH,total} = 1.61^{+0.91}_{-0.59} \times 10^{-6} h_{67.77}^3$. This implies that $0.007^{+0.005}_{-0.003} h_{67.77}^3$ percent of the baryons are contained in SMBHs at the centers of galaxies in the local universe (see Table 2).

5. DISCUSSION

Figure 11 shows the comparison of our early-type BHMF with previously estimated early-type BHMFs (Graham et al. 2007; Marconi et al. 2004; Vika et al. 2009). Our early-type BHMF is expected to be consistent with that of Graham et al. (2007) within the uncertainties, since they are both derived from the same M_{bh} - n relation. The data points are in overall good agreement within their uncertainties. There is an apparent disagreement below $M_{bh} < 10^{6.5} M_\odot$, which corresponds to $n \approx 1.5$ and the region between $10^8 M_\odot < M_{bh} < 10^{8.75} M_\odot$. Graham et al. (2007) defined early-type galaxies as $\frac{B}{T} > 0.4$ and used the GIM2D-derived n values (Allen et al. 2006), which were obtained from the logical filter for Sérsic + exponential catalog. For galaxies with $n < 1.5$, this logical filter classifies galaxies as pure disk and therefore fits them with a single component. However, we obtained $1 < n < 1.5$ for seven S0 galaxies but still performed a two-component fit. As a result, our BHMF has higher density for the low mass end ($M_{bh} < 10^{6.5} M_\odot$) and lower density for intermediate masses ($10^8 M_\odot < M_{bh} < 10^{8.75} M_\odot$). Differences in the definition of early-type galaxies and the profile fitting methodology may explain the disagreement between the two BHMFs derived from the same relation. It should also be noted that they used a sample of 1356 early-type galaxies from the Millennium Galaxy Catalogue (MGC) in the redshift range of $0.013 < z < 0.18$, and they estimated the BHMF by summing the SMBH mass distribution times an associated space-density weights, i.e., $\phi(M) = \sum W(L)M$, where $W(L) = \phi(L)/N(L)$ is constructed for black holes derived from early-type galaxies (defined as $\frac{B}{T} > 0.4$). Although the volume of their sample is considerably higher than ours, and their sample selection and BHMF estimation method are different from ours, overall their BHMF is consistent with our findings.

We also compared our BHMF with the work of Vika et al. (2009). They used the sample identical to

that of Graham et al. (2007), except they included the galaxies with $\mathfrak{M}_B > -18$, indicating the data from this region is unreliable. They used the linear M_{bh} - L_{Bulge} relation reported by Graham (2007) with dust correction to their sample. Other than using the M_{bh} - L_{Bulge} relation to derive the BHMF, their BHMF estimation method is identical to that of Graham et al. (2007). However, their BHMF does not agree well with that of Graham et al. (2007), or with ours. They discussed the probable reasons for the discrepancy between theirs and that of Graham et al. (2007) (see Section 3.1 in Vika et al. (2009)). In addition, Graham & Scott (2013) recently revised the M_{bh} - L_{Bulge} relation and found a log quadratic nature in the M_{bh} - L_{Bulge} relation, which is also expected from the linear nature of the two distinct L_{Bulge} - n relations for elliptical galaxies and bulges, and the curved M_{bh} - n relation. This may explain the discrepancy between the BHMF derived from the linear M_{bh} - L_{Bulge} relation and the one derived from the curved M_{bh} - n relation.

In addition, we compared our BHMF with that of Marconi et al. (2004). They estimated the local BHMF for early-type galaxies based on SDSS sample of Bernardi et al. (2003), by using the linear M_{bh} - L_{Bulge} and M_{bh} - σ relations reported by Marconi & Hunt (2003) assuming the same intrinsic dispersion. They also derived the local BHMF for early-type galaxies obtained from different galaxy luminosity functions, in different photometric bands. All their local BHMFs for early-type galaxies are in remarkable agreement with ours within the uncertainties. However, they reported a discrepancy at $M_{bh} < 10^8 M_\odot$ between the BHMF derived with the Bernardi et al. (2003) luminosity function and the others (see Figure 1b in Marconi et al. (2004)). They considered this discrepancy as insignificant because this is the region where authors adopted different functional forms to fit the data to extrapolate luminosity functions of early-type galaxies. Our early-type BHMF agrees more with the one derived from the sample of Bernardi et al. (2003) at $M_{bh} < 10^8 M_\odot$ than the others.

Figure 12 shows the comparison between our BHMF for all galaxy types with those of Graham et al. (2007), Vika et al. (2009), and Marconi et al. (2004). Overall our BHMF agrees better with that of Marconi et al. (2004) within the uncertainties. It is clear that there is a disagreement between ours and those of Graham et al. (2007) and Vika et al. (2009) at the low-mass end. Late-type galaxies have the biggest contribution on the BHMF at the low-mass end (see Figure 10), where the Sérsic index is more difficult to measure due to the complex nature of these late-type galaxies as we explained earlier in this paper. It is also worth mentioning that Vika et al. (2009) argued that their BHMF data below $\log(M_{bh}/M_\odot) = 7.67$ (light blue circles in Figure 12) is not reliable because it is derived from galaxies with $\mathfrak{M}_B > -18$. Our entire sample consists of galaxies with $\mathfrak{M}_B \leq -19.12$. Moreover, Davis et al. (2014) stated a possible bias for the sample of Vika et al. (2009), pointing the small number of late-type galaxies in their considerably larger sample volume (see Section 7 in Davis et al. (2014)). Although our sample does not contain very faint galaxies ($\mathfrak{M}_B > -19.12$), our BHMF results in a higher number density for the low-mass end when compared to those of Vika et al. (2009) and

Graham et al. (2007). In addition, other relations (M_{bh} - n , M_{bh} - L_{Bulge} , and M_{bh} - σ relations) are not as accurate as the M_{bh} - P relation in this mass regime (Berrier et al. 2013).

Finally, Figure 13 shows the comparison between our all-type BHMF with more recent BHMF estimates (Shankar et al. 2013b; Sijacki et al. 2015). At the high-mass end, it looks as if our BHMF lies between those of Marconi et al. (2004) and Shankar et al. (2013b), except for the lower mass SMBHs with $M_{bh} < 10^7 M_\odot$. Shankar et al. (2013b) derived the local BHMF based on the assumption that all local galaxies follow the early-type M_{bh} - σ relation reported by McConnell & Ma (2013). As shown in Figure 10, early-type galaxies dominate at the high-mass end, therefore a BHMF derived from a relation for early-type galaxies is expected to be more reliable at the high-mass end. Observational uncertainties increase for low mass (late-type) galaxies because measuring σ in disc galaxies is not a trivial task and one needs to properly count the contribution from the motion of disc and bar that is coupled with the bulge. In addition, the majority of low mass galaxies may host pseudobulges (Fisher & Drory 2011), and a number of independent groups claimed that the properties measured for galaxies with pseudobulges do not follow the typical scaling relations (e.g. M_{bh} - σ , M_{bh} - M_{Bulge} , M_{bh} - L_{Bulge}), with SMBH masses being often significantly smaller than what is expected by these relations (e.g. Hu 2009; Greene et al. 2010; Kormendy et al. 2011; Beifiori et al. 2012). Therefore, the BHMF of Shankar et al. (2013b) (and most of previous ones) likely represents an upper limit on the true local BHMF (Shankar et al. 2013b). To address this issue, Shankar et al. (2013b) re-estimated the BHMF with the same relation, but this time the authors made the odd assumption that Sa galaxies do not host any SMBHs. This assumption likely makes this modified BHMF a lower limit on the local BHMF (Sijacki et al. 2015). Our BHMF indeed stays between the BHMF of Shankar et al. (2013b) and the modified one. In the comparison with the BHMFs derived from accretion models, the continuity equation models of Shankar et al. (2013a) predict a local BHMF similar to that of Shankar et al. (2013b) when a constant Eddington ratio is assumed (see Figure 2 of Shankar et al. (2013b)), and they predict a local BHMF very similar to ours for the highest mass regime when a Eddington ratio is assumed to be decreasing as a function of cosmological time (see dot-dashed line in Figure 13). Finally, when compared with the Illustris Simulation, which is a large scale cosmological simulation with the resolution of a $(106.5 \text{ Mpc})^3$ volume, our result agrees quite well with their BHMF. At higher masses, the simulation estimate is in a remarkable agreement with our result. Similar to the others, disagreements exist at lower masses, and Sijacki et al. (2015) already argued that the simulation results are least reliable at the low-mass end (see Section 3.3 in Sijacki et al. (2015)). In summary, for the intermediate and high mass SMBHs ($M_{bh} > 10^7 M_\odot$), the agreements between our BHMF and those of previous BHMF estimates are encouraging. At the low-mass end, inconsistencies exist in the previous work that still need to be resolved, but our work is more in line with the expectations based on accre-

tion models (Shankar et al. 2013a), favouring steadily decreasing Eddington ratios, and semi-analytic models (e.g. Marulli et al. 2008), which suggest a relatively flat distribution for $M_{bh} \lesssim 10^8 M_\odot$. Also, our results at the low-mass end of the BHMf are probably consistent with the claims that the majority of low-mass galaxies contain pseudobulges rather than classical bulges (Fisher & Drory 2011). This, in turn, may explain why the M_{bh} - P produces a tighter relation than the M_{bh} - σ relation for disc galaxies (Berrier et al. 2013), and therefore why our BHMf result shows more promise when compared to expectations from semi-analytical models. This highlights an important need for properly accounting for the affects of pseudobulges in disc galaxies when determining the local BHMf.

6. CONCLUSION

The observational simplicity of our approach and the use of the statistically tightest correlations with SMBH mass, which are the Sérsic index for E/S0 galaxies and pitch angle for spiral galaxies, make it straightforward to estimate a local BHMf through imaging data only

within a limiting luminosity (redshift-independent) distance $D_L = 25.4$ Mpc ($z = 0.00572$) and a limiting absolute B-band magnitude of $\mathfrak{M}_B = -19.12$. The inconsistencies at the low-mass end of the local BHMf exist in the previous works that still need to be resolved. We presented our BHMf as of a particular interest because it is a nearly complete sample within set limits and provides reliable data, especially for the low-mass end of the local BHMf.

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FIG. 1.— **Left:** Luminosity distance vs absolute B-band magnitude for all type galaxies (606) found using the magnitude-limiting selection criteria ($B_T \leq 12.9$ and $\delta < 0$). The upper limit absolute magnitude is modeled as the same exponential in Davis et al. (2014) and is plotted here as the solid black solid line. The dashed red rectangle shows the galaxies in the volume-limited sample. **Right:** Histograms showing the number of galaxies (spiral galaxies: blue; early-types (E/S0): red; all-types: pink) contained in the limits of luminosity distance and absolute B-band magnitude as the limits are allowed to change on the exponential line based on the limiting luminosity distance. Note that the peak for all galaxy types appears in the histogram with 217 galaxies at $D_L = 28.05$ Mpc. Black dashed line represents $D_L = 25.4$ Mpc that is the limit used in Davis et al. (2014), and gives 208 galaxies (68 E/S0 + 140 spiral), which is very close to the actual peak. Using $D_L = 25.4$ Mpc allows us to be complete for dimmer galaxies. Complete volume-limited samples were computed for limiting luminosity distances in increments of 0.001 Mpc.

FIG. 2.— Our luminosity function (LF) (red triangles) is shown, in comparison with the LFs for the much larger sample of Blanton et al. (2003) (blue dots), Bernardi et al. (2013) (green dashed line), and CGS (black stars) (Ho et al. 2011). Our LF implies an overdense region for our volume-limited sample, therefore we renormalized our LF by adding -0.25 in the y-axis. The normalized LF is depicted by pink circles. Note that the LFs of Blanton et al. (2003) and Bernardi et al. (2013) have been shifted by $B - r = 0.67$ mag, the average color of an Sbc spiral (Fukugita et al. 1995), which is roughly the median Hubble type of both CGS and our volume-limited sample, and also transformed to $H_0 = 67.77$ km s $^{-1}$ Mpc $^{-1}$.

FIG. 3.— **Top:** Distribution of morphological types in CGS. **Bottom:** Distribution of morphological types in our volume-limited sample. Our sample preserves the distribution of morphological types in CGS.

FIG. 4.— The T-type histograms for our volume-limited sample and CGS are shown. Our sample preserves the T-type distribution in CGS. The differences between the densities of each T-type are always less than 5% .

FIG. 5.— This is the illustration of the methodology for estimating the errors on the model parameters. The galaxy profile (red dots), the galaxy profile+sky standard deviation (black dots), and the galaxy profile–sky standard deviation (blue dots) are shown with their best model fits for each galaxy. The differences between the radial profiles from the observed galaxy and its models are also shown below each panel. **Left** panel shows the Sérsic bulge models (dashed lines) for the elliptical galaxy (NGC1439). The red one refers to the Sérsic bulge model with $R_e = 57.02$, $n = 4.98$, and $\mu_e = 22.65$, the black one refers to the model with $R_e = 82.98$, $n = 5.56$, and $\mu_e = 23.28$, and the blue one refers to the model with $R_e = 41.34$, $n = 4.48$, and $\mu_e = 22.10$. **Right** panel shows the total galaxy models (dashed lines) of Sérsic bulge models (dotted lines) and exponential disc models (dot-dashed lines) for the lenticular galaxy (ES0208-G021). The red dashed line refers to the model with $R_e = 14.02$, $n = 2.37$, $\mu_e = 19.12$, $R_{disk} = 77.77$, and $\mu_0 = 22.26$, the black one refers to the model with $R_e = 14.39$, $n = 2.40$, $\mu_e = 19.16$, $R_{disk} = 116.23$, and $\mu_0 = 22.33$, the blue one refers to the model with $R_e = 12.61$, $n = 2.20$, $\mu_e = 18.95$, $R_{disk} = 39.35$, and $\mu_0 = 21.44$.

FIG. 6.— The surface brightness profiles for 30 elliptical galaxies are shown with the best-fit galaxy models. The dashed line is the best Sérsic fit to the bulge. The differences between the radial profiles from the observed galaxy and its model are also shown below each panel.

FIG. 7.— The surface brightness profiles for 38 S0 galaxies are shown with the best-fit galaxy model (black dashed line). The pink dotted line is the Sérsic fit to the bulge, the blue dot-dashed line is the exponential disc fit. The differences between the radial profiles from the observed galaxy and its model are also shown below each panel.

FIG. 8.— The Sérsic index histogram (blue dashed line) and the PDF fits (red solid line from PEARSDF, pink solid line from ALLFITDIST) to the data are shown. The PDF (red solid line) from PEARSDF is defined by the statistical standardized moments: $\mu = 3.10$, $stdev = 1.38$, $skewness = 0.95$, and $kurtosis = 4.17$. The PDF (pink solid line) from ALLFITDIST is a gamma distribution function with $\mu = 3.11$, $variance = 1.84$, shape $a = 5.26$, scale $b = 0.59$.

FIG. 9.— **Left:** Impact of the uncertainties on the shape of the BHMF is shown, first assuming no errors, then allowing the listed errors to be perturbed individually and then collectively. The uncertainties in the Sérsic index distribution have no impact on the BHMF for $M_{bh} > 10^9 M_\odot$. The uncertainties in the M_{bh} - n relation dominate at this region, softening the high-mass decrease of the BHMF, and thus increasing the total density of the BHMF for high masses. **Right:** Best estimate of the early-type BHMF is obtained by merging all the MCMC realizations of the BHMFs after allowing the listed errors to be perturbed collectively. The solid red line represents the 50th percentile and the green shaded region is delimited by the 16th and 84th percentile levels. Note that the BHMF estimates are all normalized by adding -0.25 in the y-axis to be able correct for the overdensity in our survey volume.

FIG. 10.— Best estimate of the BHMF is obtained by merging all the MCMC realizations of the BHMFs from the early- and late-type galaxies. The M_{bh} - n and M_{bh} - P relations are used for the early- and late-type galaxies, respectively. The MCMC sampling is used to account for the uncertainties from both the measurements and the scaling relations. The all-type BHMF (red solid line) is defined by the 50th percentile, while its error region (green shaded region) is delimited by the 16th and 84th percentile levels of the merged MCMC realizations. The blue and pink dotted lines show the 1σ uncertainty region for the late- and early-type BHMF, respectively. This clearly shows that the late-type BHMF dominates at the low-mass end while the early-type BHMF dominates at the high-mass end. Note that the BHMF estimates are all normalized by adding -0.25 in the y-axis.

FIG. 11.— Comparison of our early-type BHMF (solid red line) with a green shaded $\pm 1\sigma$ error region; with those of Graham et al. (2007) (pink triangles: GR07); Marconi et al. (2004) (black stars: M04); and Vika et al. (2009) (blue open circles: V09). The BHMF data of Vika et al. (2009) below $\log(M_{bh}/M_\odot) = 7.67$, which Vika et al. (2009) considers unreliable because it is derived from galaxies with $\mathfrak{M}_B > -18$, is depicted by the open circles with light blue color. Note that our BHMF is normalized by adding -0.25 in the y-axis to be able correct for the overdensity in our sample and all other BHMFs are transformed to $H_0 = 67.77$ km s $^{-1}$ Mpc $^{-1}$.

FIG. 12.— Comparison of our determination of the BHMf (red solid line) for all galaxy types with a green shaded $\pm 1\sigma$ error region; with those of Graham et al. (2007) (pink triangles: GR07); Marconi et al. (2004) (black stars: M04); and Vika et al. (2009) (blue open circles: V09). The BHMf data of Vika et al. (2009) below $\log(M_{bh}/M_\odot) = 7.67$, which Vika et al. (2009) considers unreliable because it is derived from galaxies with $\mathfrak{M}_B > -18$, is depicted by the open circles with light blue color. Note that our BHMf is normalized by adding -0.25 in the y-axis to be able correct for the overdensity in our sample and all other BHMfs are transformed to $H_0 = 67.77 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

FIG. 13.— Comparison of our determination of the BHMf (red solid line) for all galaxy types with a green shaded $\pm 1\sigma$ error region with more recent works. The blue solid lines show the 1σ uncertainty region for the local BHMf from Shankar et al. (2013b)(S13), assuming the revised M_{bh} - σ relation from McConnell & Ma (2013) and applying it to all local galaxies. The region enclosed by the blue dashed lines is the same but assuming the SMBH mass in Sa galaxies is negligible. The black dot-dashed line shows the local BHMf derived by using the continuity equation models of Shankar et al. (2013a) and assuming a characteristic Eddington ratio decreasing with cosmological time. The pink dotted line marks the local BHMf in the Illustris simulated volume (Sijacki et al. 2015). Note that our BHMf is normalized by adding -0.25 in the y-axis to be able correct for the overdensity in our sample and all other BHMfs are transformed to $H_0 = 67.77 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

TABLE 1
BHMF VALUES

$\log M_{bh}/M_{\odot}$ (1)	$\log \varphi [h_{67.77}^3 Mpc^{-3} dex^{-1}]$ Early type (2)	$Mpc^{-3} dex^{-1}$ All galaxies (3)
5.00	$-4.42^{+0.27}_{-0.31}$	$-3.84^{+0.30}_{-0.39}$
5.25	$-4.29^{+0.25}_{-0.31}$	$-3.66^{+0.24}_{-0.35}$
5.50	$-4.18^{+0.24}_{-0.28}$	$-3.48^{+0.22}_{-0.31}$
5.75	$-4.08^{+0.22}_{-0.26}$	$-3.30^{+0.19}_{-0.25}$
6.00	$-3.96^{+0.20}_{-0.24}$	$-3.14^{+0.14}_{-0.22}$
6.25	$-3.84^{+0.17}_{-0.22}$	$-3.00^{+0.11}_{-0.18}$
6.50	$-3.73^{+0.15}_{-0.19}$	$-2.88^{+0.07}_{-0.13}$
6.75	$-3.62^{+0.13}_{-0.17}$	$-2.80^{+0.06}_{-0.08}$
7.00	$-3.51^{+0.11}_{-0.14}$	$-2.74^{+0.06}_{-0.07}$
7.25	$-3.41^{+0.08}_{-0.12}$	$-2.72^{+0.08}_{-0.11}$
7.50	$-3.32^{+0.07}_{-0.09}$	$-2.75^{+0.12}_{-0.15}$
7.75	$-3.25^{+0.06}_{-0.06}$	$-2.85^{+0.16}_{-0.17}$
8.00	$-3.21^{+0.07}_{-0.06}$	$-2.97^{+0.17}_{-0.16}$
8.25	$-3.20^{+0.08}_{-0.09}$	$-3.09^{+0.16}_{-0.15}$
8.50	$-3.27^{+0.11}_{-0.16}$	$-3.25^{+0.15}_{-0.18}$
8.75	$-3.45^{+0.17}_{-0.27}$	$-3.44^{+0.17}_{-0.28}$
9.00	$-3.71^{+0.25}_{-0.39}$	$-3.70^{+0.25}_{-0.39}$
9.25	$-4.02^{+0.35}_{-0.46}$	$-3.99^{+0.34}_{-0.50}$
9.50	$-4.32^{+0.39}_{-0.64}$	$-4.32^{+0.42}_{-0.59}$

NOTE. — Columns: (1) SMBH mass listed as $\log(M/M_{\odot})$ in 0.25 dex intervals. (2) Normalized BHMF data for early-type galaxies in our sample, as presented in Figure 9 (left), in units of $h_{67.77}^3 Mpc^{-3} dex^{-1}$. (3) Normalized BHMF data for all galaxies in our sample, as presented in Figure 10, in units of $h_{67.77}^3 Mpc^{-3} dex^{-1}$.

TABLE 2
BLACK HOLE MASS FUNCTION EVALUATION

N	M_{Total}	ρ	Ω_{BH}	Ω_{BH}/ω_b
(1)	($10^{10} M_\odot$) (2)	($10^5 h_{67.77}^3 M_\odot \text{ Mpc}^{-3}$) (3)	($10^{-6} h_{67.77}$) (4)	($h_{67.77}^3 \%$) (5)
68 (E/S0) ^b	$1.05^{+0.47}_{-0.36}$	$3.10^{+1.40}_{-1.06}$	$2.44^{+1.10}_{-0.83}$	$0.011^{+0.005}_{-0.004}$
68 (E/S0) ^a	$0.59^{+0.26}_{-0.20}$	$1.74^{+0.79}_{-0.60}$	$1.37^{+0.62}_{-0.47}$	$0.006^{+0.003}_{-0.002}$
140 (Spiral) ^{*,b}	$0.18^{+0.22}_{-0.09}$	$0.55^{+0.65}_{-0.27}$	$0.43^{+0.51}_{-0.21}$	$0.002^{+0.003}_{-0.002}$
140 (Spiral) ^a	$0.10^{+0.12}_{-0.05}$	$0.30^{+0.37}_{-0.15}$	$0.24^{+0.29}_{-0.12}$	$0.001^{+0.002}_{-0.001}$
208 (All-type) ^b	$1.23^{+0.69}_{-0.45}$	$3.65^{+2.05}_{-1.33}$	$2.87^{+1.60}_{-1.11}$	$0.013^{+0.008}_{-0.006}$
208 (All-type) ^a	$0.69^{+0.38}_{-0.25}$	$2.04^{+1.16}_{-0.75}$	$1.61^{+0.91}_{-0.59}$	$0.007^{+0.005}_{-0.003}$

NOTE. — Columns: (1) Number of galaxies. (2) Total mass from the summation of all the SMBHs in units of $10^{10} M_\odot$. (3) Density of SMBHs in units of $10^5 h_{67.77}^3 M_\odot \text{ Mpc}^{-3}$. (4) Cosmological SMBH mass density [$\Omega_{BH} = \rho/\rho_0$, assuming $\rho_0 = 3H_0^2/8\pi G = 1.274 \times 10^{11} M_\odot \text{ Mpc}^{-3}$ when $H_0 = 67.77 \text{ km s}^{-1} \text{ Mpc}^{-3}$]. (5) Fraction of the universal baryonic inventory locked up in SMBHs [Ω_{BH}/ω_b].

^b Before the normalization is applied

^a After the normalization is applied

^{*} Data taken from Davis et al. (2014)

TABLE 3
VOLUME LIMITED SAMPLE

Galaxy Name (1)	Hubble Type (2)	D_L (3)	B_T (4)	Band (5)	R_e/FWHM (6)	n (7)	$\log(M/M_\odot)$ (8)	Telescope (9)
ESO 208–G021	S0*	17.0	−19.57	R	14	$2.37^{+0.03}_{-0.17}$	$7.57^{+0.02}_{-0.14}$	LCO
ESO 221–G026	E	12.4	−19.13	H	30	$4.11^{+0.58}_{-0.78}$	$8.43^{+0.15}_{-0.29}$	2MASS
ESO 311–G012	S0/a	18.3	−20.24	H	6	$1.91^{+0.55}_{-0.36}$	$7.13^{+0.51}_{-0.48}$	2MASS
IC 5181	S0	24.8	−19.38	H	2	$1.35^{+0.19}_{-0.04}$	$6.32^{+0.32}_{-0.08}$	2MASS
NGC 584	E	19.5	−20.07	H	29	$4.08^{+0.83}_{-0.43}$	$8.42^{+0.21}_{-0.15}$	2MASS
NGC 596	S0*	20.6	−19.68	H	3	$2.84^{+0.26}_{-0.71}$	$7.89^{+0.14}_{-0.53}$	2MASS
NGC 636	E	25.4	−19.62	H	13	$7.15^{+0.19}_{-0.91}$	$8.93^{+0.02}_{-0.09}$	2MASS
NGC 720	E	23.9	−20.54	H	25	$2.53^{+0.36}_{-0.28}$	$7.69^{+0.23}_{-0.22}$	2MASS
NGC 936	S0/a	20.7	−20.55	H	10	$2.63^{+0.22}_{-0.45}$	$7.76^{+0.13}_{-0.35}$	2MASS
NGC 1052	E	19.6	−19.93	3.6 μm	14	$2.99^{+0.49}_{-0.26}$	$7.97^{+0.23}_{-0.15}$	Spitzer
NGC 1172	E	24.3	−19.30	F160W	41	$3.63^{+0.19}_{-0.18}$	$8.26^{+0.07}_{-0.97}$	HST
NGC 1201	S0*	20.2	−19.52	R	5	$1.38^{+0.10}_{-0.06}$	$6.38^{+0.34}_{-0.31}$	LCO
NGC 1291	S0/a	8.6	−20.12	H	9	$1.60^{+0.20}_{-0.13}$	$6.74^{+0.27}_{-0.20}$	2MASS
NGC 1302	S0/a	20.0	−19.62	3.6 μm	11	$3.29^{+0.11}_{-0.17}$	$8.12^{+0.05}_{-0.08}$	Spitzer
NGC 1316	S0	19.2	−21.71	H	23	$2.32^{+0.94}_{-0.15}$	$7.65^{+0.53}_{-0.12}$	2MASS
NGC 1326	S0/a	16.9	−19.68	3.6 μm	7	$2.21^{+0.21}_{-0.05}$	$7.47^{+0.17}_{-0.04}$	Spitzer
NGC 1332	E*	18.9	−20.11	3.6 μm	20	$4.05^{+0.25}_{-0.25}$	$8.41^{+0.23}_{-0.23}$	Spitzer
NGC 1340	E	18.2	−20.14	H	42	$4.04^{+0.92}_{-0.62}$	$8.41^{+0.23}_{-0.23}$	2MASS
NGC 1351	E*	20.4	−19.17	F160W	32	$2.57^{+0.14}_{-0.13}$	$7.72^{+0.09}_{-0.10}$	HST
NGC 1374	E	19.4	−19.46	H	12	$4.59^{+0.18}_{-0.84}$	$8.56^{+0.04}_{-0.25}$	2MASS
NGC 1379	E	18.1	−19.39	H	14	$3.56^{+0.21}_{-0.27}$	$8.24^{+0.08}_{-0.11}$	2MASS
NGC 1380	S0	18.0	−20.29	K	12	$2.02^{+0.53}_{-0.12}$	$7.26^{+0.45}_{-0.13}$	2MASS
NGC 1387	S0*	18.0	−19.56	H	3	$2.72^{+0.56}_{-0.46}$	$7.82^{+0.30}_{-0.34}$	2MASS
NGC 1395	E	21.9	−21.11	H	33	$3.68^{+0.39}_{-0.63}$	$8.28^{+0.13}_{-0.28}$	2MASS
NGC 1399	E	18.9	−21.10	H	34	$4.63^{+0.63}_{-1.07}$	$8.57^{+0.13}_{-0.33}$	2MASS
NGC 1400	E*	23.6	−19.81	F160W	21	$2.09^{+0.05}_{-0.07}$	$7.32^{+0.05}_{-0.07}$	HST
NGC 1404	S0*	18.6	−20.49	3.6 μm	10	$2.86^{+0.11}_{-0.62}$	$7.90^{+0.06}_{-0.44}$	Spitzer
NGC 1407	E	23.8	−21.22	H	45	$4.39^{+0.91}_{-0.80}$	$8.51^{+0.20}_{-0.26}$	2MASS
NGC 1427	E	20.9	−19.80	R	52	$5.02^{+0.83}_{-0.76}$	$8.65^{+0.14}_{-0.18}$	LCO
NGC 1439	E	24.3	−19.65	R	56	$4.98^{+0.58}_{-0.50}$	$8.65^{+0.10}_{-0.11}$	LCO
NGC 1452	S0/a	22.8	−19.24	4.5 μm	5	$1.62^{+0.11}_{-0.04}$	$6.77^{+0.15}_{-0.06}$	Spitzer
NGC 1527	S0*	16.7	−19.49	J	6	$1.91^{+0.23}_{-0.22}$	$7.14^{+0.24}_{-0.28}$	2MASS
NGC 1533	S0*	18.4	−19.56	3.6 μm	3	$1.23^{+0.04}_{-0.03}$	$6.09^{+0.07}_{-0.07}$	Spitzer
NGC 1537	E*	18.8	−19.82	H	16	$2.89^{+0.86}_{-0.37}$	$7.92^{+0.39}_{-0.24}$	2MASS
NGC 1543	S0	17.5	−19.78	H	7	$1.15^{+0.04}_{-0.26}$	$5.91^{+0.09}_{-0.72}$	2MASS
NGC 1549	E	16.4	−20.43	H	23	$5.62^{+1.21}_{-0.91}$	$8.76^{+0.15}_{-0.17}$	2MASS
NGC 1553	S0	14.6	−20.57	4.5 μm	9	$1.78^{+0.32}_{-0.81}$	$7.73^{+0.20}_{-0.75}$	Spitzer
NGC 1574	S0*	18.6	−20.05	H	8	$1.68^{+0.06}_{-0.15}$	$6.85^{+0.08}_{-0.22}$	2MASS
NGC 2217	S0/a	19.5	−20.04	H	5	$1.24^{+0.04}_{-0.46}$	$6.11^{+0.08}_{-1.33}$	2MASS
NGC 2325	E	22.6	−19.82	R	54	$2.73^{+0.35}_{-0.15}$	$7.82^{+0.20}_{-0.10}$	LCO
NGC 2380	S0	22.2	−20.54	H	10	$3.28^{+0.10}_{-0.05}$	$8.12^{+0.04}_{-0.02}$	2MASS
NGC 2434	E	21.9	−20.23	H	14	$5.03^{+0.97}_{-1.34}$	$8.65^{+0.16}_{-0.37}$	2MASS
NGC 2640	E*	17.2	−20.13	H	26	$3.82^{+0.47}_{-0.40}$	$8.33^{+0.15}_{-0.15}$	2MASS
NGC 2784	S0	8.5	−19.22	H	15	$3.79^{+0.54}_{-0.69}$	$8.32^{+0.17}_{-0.29}$	2MASS
NGC 2822	S0*	24.7	−20.62	R	6	$1.60^{+0.01}_{-0.03}$	$6.74^{+0.01}_{-0.04}$	LCO
NGC 2974	S0*	25.3	−20.30	R	18	$3.23^{+0.40}_{-0.22}$	$8.10^{+0.17}_{-0.11}$	LCO
NGC 3115	S0*	10.1	−20.09	3.6 μm	11	$2.11^{+0.58}_{-0.39}$	$7.34^{+0.46}_{-0.44}$	Spitzer
NGC 3136	E	23.9	−20.93	R	92	$4.77^{+0.74}_{-0.56}$	$8.60^{+0.14}_{-0.14}$	LCO
NGC 3585	E	17.6	−20.63	H	35	$3.85^{+0.91}_{-0.68}$	$8.34^{+0.25}_{-0.28}$	2MASS
NGC 3904	E	24.7	−20.28	3.6 μm	20	$3.23^{+0.77}_{-0.23}$	$8.10^{+0.30}_{-0.12}$	Spitzer
NGC 3923	E	20.9	−21.13	H	19	$3.12^{+0.60}_{-0.09}$	$8.04^{+0.26}_{-0.05}$	2MASS
NGC 3955	S0/a	20.6	−19.15	3.6 μm	12	$2.50^{+0.10}_{-0.53}$	$7.67^{+0.07}_{-0.46}$	Spitzer
NGC 4024	E*	25.4	−19.34	H	12	$4.74^{+5.20}_{-0.80}$	$8.59^{+0.47}_{-0.22}$	2MASS
NGC 4546	S0*	17.3	−19.74	3.6 μm	8	$2.51^{+0.20}_{-0.20}$	$7.67^{+0.14}_{-0.16}$	Spitzer
NGC 4684	S0/a	20.5	−19.38	H	7	$3.44^{+0.20}_{-0.20}$	$8.19^{+0.08}_{-0.09}$	2MASS
NGC 4691	S0/a	22.5	−19.83	3.6 μm	10	$1.12^{+0.02}_{-0.09}$	$5.82^{+0.05}_{-0.23}$	Spitzer
NGC 4697	E	11.6	−20.00	H	47	$3.02^{+0.38}_{-0.32}$	$7.99^{+0.18}_{-0.19}$	2MASS

TABLE 3 — *Continued*

Galaxy Name (1)	Hubble Type (2)	D_L (3)	B_T (4)	Band (5)	R_e/FWHM (6)	n (7)	$\log(M/M_\odot)$ (8)	Telescope (9)
NGC 4753	S0	19.6	-20.46	$3.6\mu\text{m}$	16	$3.86^{+0.38}_{-0.15}$	$8.35^{+0.12}_{-0.05}$	Spitzer
NGC 4856	S0/a	21.1	-20.36	K	13	$2.79^{+0.33}_{-0.29}$	$7.86^{+0.18}_{-0.19}$	2MASS
NGC 4958	S0	20.9	-20.03	$3.6\mu\text{m}$	10	$2.25^{+0.13}_{-0.04}$	$7.47^{+0.11}_{-0.03}$	Spitzer
NGC 4976	E	12.5	-20.20	J	58	$4.22^{+0.61}_{-0.58}$	$8.46^{+0.15}_{-0.19}$	2MASS
NGC 4984	S0*	21.3	-19.62	$4.5\mu\text{m}$	9	$4.46^{+0.09}_{-1.27}$	$8.53^{+0.02}_{-0.45}$	Spitzer
NGC 5128	S0	3.7	-20.53	H	20	$1.54^{+0.44}_{-0.37}$	$6.65^{+0.56}_{-0.70}$	2MASS
NGC 6684	S0	12.4	-19.4	H	4	$2.60^{+0.25}_{-0.39}$	$7.74^{+0.16}_{-0.30}$	2MASS
NGC 7041	S0*	24.9	-19.81	R	7	$1.85^{+0.34}_{-0.23}$	$7.07^{+0.35}_{-0.30}$	LCO
NGC 7144	S0*	24.9	-20.35	H	3	$2.42^{+0.34}_{-0.23}$	$7.61^{+0.23}_{-0.19}$	2MASS
NGC 7145	S0*	23.1	-19.32	R	11	$2.45^{+0.10}_{-0.35}$	$7.63^{+0.07}_{-0.30}$	LCO
NGC 7507	E	22.5	-20.35	K	16	$5.83^{+1.33}_{-0.64}$	$8.79^{+0.15}_{-0.10}$	2MASS

NOTE. — Columns: (1) Galaxy name. (2) Hubble type, from <http://cgs.obs.carnegiescience.edu/CGS/database/tables>. (3) Luminosity distance in Mpc, compiled from the mean redshift-independent distance from MED. (4) B-band absolute magnitude, determined from formula: $\mathfrak{M}_B = B_T - 5 \log(D_L) + 5 - A_B$, where B_T is total B-band apparent magnitude (taken from *HyperLeda*), A_B is galactic extinction in B-band (from Schlafly & Finkbeiner (2011), as compiled by the MED), and D_L is luminosity distance in units of pc. (5) Band. (6) R_e/FWHM ratio. (7) Sérsic Index. (8) SMBH mass in $\log(M/M_\odot)$, converted from the Sérsic index via the Equation 1. (9) Telescope from which the imaging data was taken.

*

Hubble type for this galaxy is determined based on its light profile.